

Force sensor

This invention relates to a force sensor according to the preamble of claim 1.

5 The present invention covers the field of measuring a force with a system in the micro- or nano-regime. Micro electro-mechanical force sensors are available in a plurality of principles. They differ by the detection mechanisms. Known sensors are based on piezoresistive, capacitive, tunnel
10 current or thermal principles. These known force sensors are relatively large, that is they have large dimensions as some multiples of 100 μm . Force sensors according to the state-of-the-art are disclosed in the documents [5] and [6], in which limits to its size that is limits to a further miniaturization can be derived. In the context of the present inven-
15 tion force sensors are also denoted by «inertial sensors».

In paper [1] furthermore all the problems which arise due to the increasing miniaturization of force sensors are dis-
20 cussed. The principle of a capacitive force sensor is depicted in Fig. 4(a): Due to the influence of a force

$$F = m \cdot a ,$$

where m denotes the mass and a the effecting acceleration, a change Δx of the distance x_0 of two electrodes or plates A
25 will occur. The capacity C is also determined by the dielectric constant ϵ_0 as well as by number ϵ_r , which is determined by the dielectric material between the plates A . These capacitive sensors show in general a degradation of the resolution by miniaturization. This effect results one the
30 one hand from a not very suitable signal to noise ratio (SNR). On the other hand the actual cause is an overproportional scaling down of the forces as well as restrictions due to process limitations and design rules. They are also called miniaturization barriers. The
35 limitations prevent that the scaling down of forces can be compensated by a corresponding miniaturization of the distance x_0 of the electrodes.

A numeric example explains the draw back of the state-of-the-art sensor according to figure 4(a):

$$\begin{aligned}x_0 &= 1 \text{ } \mu\text{m}; \\5 \quad \Delta x &= 0,05 \text{ } \mu\text{m}; \\C_0 &= 0.53 \text{ pF}; \\A &= 6 \cdot 10^4 \text{ } \mu\text{m}^2.\end{aligned}$$

The displacement of the plates by $\Delta x = 0,05 \text{ } \mu\text{m}$ results in a relative change of capacitance $\Delta C_{\text{rel}} \approx 5\%$.

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Furthermore the increasing miniaturization of force sensors leads to the problem of a reduction of the gauge factor for measuring a force. For a capacitive force sensor a limit arises also in reduction of its seismic mass due to design rules.

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The present invention therefore addresses the problem due to the miniaturization of force sensors.

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The object of the present invention is to overcome the problems presented by the prior force sensors, especially to the degradation of the resolution.

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These problems resulting from a further miniaturization are solved by a force sensor specified in claim 1.

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By the proposed use of a nanostructure as e.g. a carbon nanotube a force sensor is provided, which increases significantly the sensitivity as well as the resolution. This improvements result from on the sensing principle based on quantum-mechanical effects. By a deformation of a nanostructure its electrical conductance is affected up to two orders of magnitude. This outstanding sensitivity of a nanostructure as e.g. a carbon nanotube is disclosed in [2].

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Further advantageous embodiments are given in dependant claims.

The invention will be now described in preferred embodiments with reference to the accompanying drawings wherein:

figure 1 is a view of a first embodiment;

5 figure 2 is a view of a first embodiment, which allows a compensation of environmental effects;

figure 3(a), Fig. 3(b)

show the principle of the deformation of a carbon nanotube;

10 figure 4(a) shows the principle of a known capacitive force sensor;

figure 4(b) discloses the principle of a force sensor according to the present invention;

figure 5 shows a carbon nanotube.

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Figure 5 illustrates the topological structure of a carbon nanotube. The aspect ratio of common carbon nanotubes is in the range 50 .. 5000. An example of the length is given below. Before explaining embodiments the properties of carbon
20 nanotubes are first briefly discussed and references to its properties and production are given.

The invention becomes apparent by considering the sensitivity of a carbon nanotube when being object of a deformation
25 caused by a force F. Sensitivity is in this context the ratio

$$\frac{\Delta G}{\Delta F}$$

where ΔG : change of conductance.

ΔF : change of force.

For a carbon nanotube 3 the conductance G instead of the
30 capacitance C is the electrical property, which is affected by the resulting deformation caused by a force. The sensitivity of a carbon nanotube 3 is up to two orders of magnitude compared to the sensitivity of a capacitive force sensor. This outstanding sensitivity and its possible causes
35 are discussed and disclosed in the document [2].

Corresponding to the values given in the introduction of this document the sensitivity of a force sensor 1 with a carbon nanotube of height h is approximately as follows:

$$\begin{aligned} h &= 0,600 \text{ } \mu\text{m}; \\ \Delta x &= 0,050 \text{ } \mu\text{m}; \\ F &= 8 \text{ nN}; \\ \Delta G_{\text{rel}} &= 99\%. \end{aligned}$$

In the publication [3] in an extensive manner the synthesis, properties and possible applications of carbon nanotubes 3 are disclosed. The teachings of this document [3] are therefore here incorporated by reference to it.

The principle of a force sensor 1 according the present invention is depicted in Fig. 3(a), 3(b) and 4(b). According to the representation in Fig. 3(a) and 3(b) a force F acts on carbon nanotube 5. A carbon nanotube 5 is carried or fixed between two arms 4. The carbon nanotube 5 itself is part of a electric circuit with a current I . A deformation Δx caused by a force F perpendicular to the carbon nanotube 3 decreases its conductance G . This results by a voltage driven measurement in a lowering of current I . The amount of the current I gives an indirect measure of the acting force F . By an external circuitry and an appropriate calibration the size of the force F can be displayed. The force F is either from an external source or caused by an movable element, which is a part of the force sensor 1. The latter principle is depicted in figure 4(b), where the movement of the element 7 is caused by an acceleration.

In table 1 shows an example of the dimensions and its parameters of a carbon nanotube, which is the basic element of the present invention. The cited values correspond to those disclosed in [2], the symbol S denotes the unit Siemens, the unit for conductance G :

Dimension, parameter	Value
Length of a carbon nanotube	500 nm
force acting perpendicular to the axis of a carbon nanotube	8 nN
displacement, deformation Δx	50 nm
conductance change ΔG	$9 \cdot 10^{-6}$ S to $9 \cdot 10^{-8}$ S

Table 1: typical parameters of a carbon nanotube.

For a force sensor 1 according to the present invention the carbon nanotube 3 may be built on the basis of a chemical vapour deposition process CVD as controlled growth on prepatterned nanostructures. Details to this processes can be derived from document [4].

Figure 1 shows a g-sensor 1 - acceleration sensor - as a first embodiment of the present invention. The sensor 1 includes a U-shaped support 2 of two arms 4 carrying carbon nanotube 3. The two arms 4 are electrically insulated at the position 6, partly shown in figure 1. A moveable element 7 of mass m is located between the arms 4. The moveable element 7 is provided with a cusp tip 11. A movement of the element 7 towards the carbon nanotube 3 is caused by a force F determined by

$$F = m \cdot a,$$

where:

m mass of element 7;

a acceleration acting via sensor 1 on element 7.

Tip 11 transfers the force F on to the carbon nanotube 3, by which force the carbon nanotube is mechanically stressed, that is deformed by a value Δx .

Optionally (not shown in figure 1) the sensor 1 is provided with at least one stop element in order to limit the movement of element 7. These stop elements enable a improved shock

resistance of the sensor 1. Each arm 4 is provided with a cusp 5, on which the carbon nanotube 3 is mounted.

5 The stability of the moveable element 7 may be increased by at least one spring 8. The spring 8 serves also for the guidance of the moveable element 7

10 A further embodiment of the present invention is depicted in Figure 2 with a second nanotube 10. The second carbon nanotube 10 may not be deformed by a force F . The arrangement with a second nanotube 10 allows the compensation of environmental effects as e.g. temperature. The second carbon nanotube is in mounted to the arms 4 in the same manner as described above. However the second carbon nanotube 10 is electrically insulated from the first one. The second carbon
15 nanotube 10 is also part of an electric circuit with a current I . By an external circuitry this arrangement allows a common mode rejection, that is the above mentioned compensation of environmental effects. Also a possible deformation of the support 2 can be compensated by using a second
20 carbon nanotube 10

Force sensors and g-sensors according to the present invention are especially suitable for Vehicle dynamic control
25 systems, but this example of application is not limiting at all.

The outstanding sensitivity of a g-sensor 1 according to the present invention allows the detection of very small accelerations, which opens a broad field of applications.
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The invention is not limited to the embodiment depicted above with a carbon nanotube. The invention can also be carried out with other elements which have similar properties as carbon
35 nanotube. Another example is a bor-nitride nanotube. It shows a huge change in electrical and optical properties by mechanical deformation as it has been shown for carbon nanotubes

[1]. In a more general context nanotubes count to the material class of quasi one-dimensional (1D) nanostructures which are characterized by the confinement of electrons in two spatial directions. These strong effects even hold for a big
 5 class of nanostructures where local atomic bonds determine the electrical and optical properties.

Therefore in this paper the elements

- carbon nanotubes;
 - 10 - nanotubes,
 - quasi one-dimensional (1D) nanostructures
- are summarized by the general term «nanostructure».

15 **List of reference numerals**

- 1 force sensor, inertial sensor
- 2 support
- 3 carbon nanotube, nanotube, bor-nitride nanotubes,
- 20 quasi one-dimensional (1D) nanostructures;
- nanostucture
- 4 arm
- 5 cusp at the arm 4, mounting point of a carbon nanotube
- 6 insulation
- 7 moveable element, mass
- 25 8 spring
- 9 insulation between nanotube 3 and 10
- 10 second carbon nanotube, second nanotube, second bor-nitride nanotubes, second quasi one-dimensional (1D) nanostructures; second nanostructure
- 30 11 tip of the moveable element 7

list of symbols

- a acceleration [m/s^2]
 ϵ_0 dielectric constant
 ϵ_r relative dielectric constant
5 F force
G conductance
m mass [g]
 x_0 distance, e.g. [μm or nm]
 Δx displacement, e.g. [μm or nm]
10 ΔC change of capacity.
 ΔF change of force.
 ΔG change of conductance

list of acronyms

- CNT carbon nanotube
15 CVD chemical vapour deposition
MEMS Microelectromechanical systems
SNR Signal to noise ratio
VDC Vehicle dynamic control

References

- 5 [1] C. Hierold,
«Micro- and Nanosystems: Review and Outlook»,
MME 2003, 14th Micromechanics Europe Workshop, Delft,
2003.
- [2] S T. W. Tombler et al.,
«Reversible electromechanical characteristics of carbon
nanotubes under loca-probe manipulation»
Nature 405, 769 (2000)
- 10 [3] S.B. Sinnott and R. Andrews,
«Carbon Nantubes: Synthesis, properties and
applications»
Critical Reviews in Solid State and Material Science,
26 (3), 145 (2001)
- 15 [4] N. R. Franklin and H. Dai,
«An enhanced CVD approach to extensive nanotube
networks with directionality»
Advanced Materials, 12, 890, (2000)
- 20 [5] C. Acar and A. M. Shkel,
«Experimental evaluation and comparative analysis of
commercial variable-capacitance MEMS accelerometers»
Journal of Micromechanics and Microengineering 13 634
(2003)
- 25 [6] N. Yazdi, F. Ayazi, K. Najafi,
«Micromachined Inertial Sensors»
Proceeding of the IEEE, Vol. 86, No. 8, August 1998